Texting while Flying: Estimating Impact of Data Comm on Mid-air Collisions with Bayesian Belief Network

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Outline

- Introduction – Data Comm
- Method for Calculating Mid-air Collisions
- Analysis Results
- Discussion
- Summary and Conclusions
- Recommendations and Future Work

Introduction

Data Comm

- Reduces controller and pilot workload
- Human memory less critical
- Increases capacity of radio frequencies
- Diminishes error and increases clarity
- Presents unique advantages and applications

```
CPDLC-MESSAGE
• 16:51-EDYY 26 ACCEPTED 01/02
SEA723 CLEARED TO KISP
VIA KFLL1 DEPARTURE
ZAPPA TRANSITION WOLFO
AR18 WETRO CEBEE SWL
J121 SARDI CCC LOVES2
---------RESPONSE---------
WILCO
*PRINT
<RETURN 18:21
```

Data Communications supplements voice communication between controllers and pilots with digital text-based messages.

Introduction

- Pilots and controllers communicate through radio voice channels, mainly.
- These communications relay many types of information including tactical commands to alter flight paths, strategic messages used to maximize longer-term flight and airspace efficiency, and routine information that is often repetitive or advisory but nonetheless required by the current air traffic control rules.
- A key pre-requisite to enhancing the capacity and efficiency of the NAS lies in providing reliable tools to controllers and pilots that reduce the workload associated with such communications.
- Nearly all future automation and operational concepts that address these issues are dependent upon the Data Communication System.

Introduction

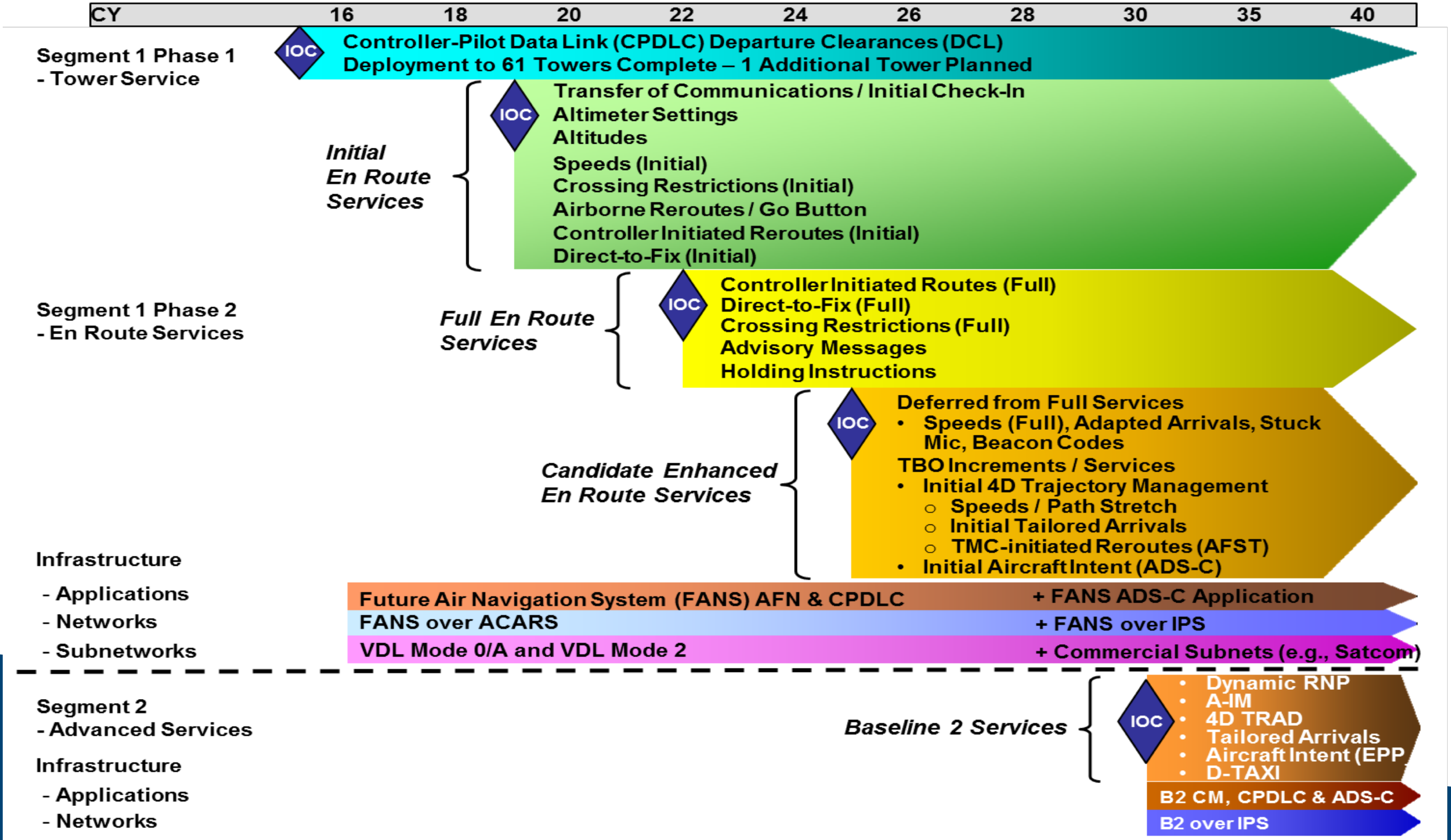
- Therefore, Data Comm has to be especially reliable and available.
- Currently, 39,000 Data Comm messages are transmitted per week
- Pre-Departure Clearances (DCL) are being transmitted by Data Comm at 62 US airports
- 4,000 aircraft equipped as of February 2018

Metrics for DCL Services at the Tower (S1P1)

- Data Comm Usage; Minutes of Comm Time; Ground Delays; Airspace Throughput; Efficiency; Fuel Burn; Implementation

Introduction

Data Comm Services Roadmap



Segment 1 Phase 1
- Tower Service

Controller-Pilot Data Link (CPDLC) Departure Clearances (DCL)
Deployment to 61 Towers Complete – 1 Additional Tower Planned

Initial En Route Services

- Transfer of Communications / Initial Check-In
- Altimeter Settings
- Altitudes
- Speeds (Initial)
- Crossing Restrictions (Initial)
- Airborne Reroutes / Go Button
- Controller Initiated Reroutes (Initial)
- Direct-to-Fix (Initial)

Segment 1 Phase 2
- En Route Services

Full En Route Services

- Controller Initiated Routes (Full)
- Direct-to-Fix (Full)
- Crossing Restrictions (Full)
- Advisory Messages
- Holding Instructions

Candidate Enhanced En Route Services

Deferred from Full Services
- Speeds (Full), Adapted Arrivals, Stuck Mic, Beacon Codes

TBO Increments / Services
- Initial 4D Trajectory Management
  - Speeds / Path Stretch
  - Initial Tailored Arrivals
  - TMC-initiated Reroutes (AFST)
- Initial Aircraft Intent (ADS-C)

Infrastructure
- Applications: Future Air Navigation System (FANS) AFN & CPDLC; + FANS ADS-C Application
- Networks: FANS over ACARS; + FANS over IPS
- Subnetworks: VDL Mode 0/A and VDL Mode 2; + Commercial Subnets (e.g., Satcom)

Segment 2
- Advanced Services

Baseline 2 Services

- Dynamic RNP
- A-IM
- 4D TRAD
- Tailored Arrivals
- Aircraft Intent (EPP
- D-TAXI

Infrastructure
- Applications: B2 CM, CPDLC & ADS-C
- Networks: B2 over IPS

Introduction

- One of the benefits of Data Comm should be the increase in *safety* from use of more efficient controller-pilot communications through digital text messaging.
- In this study we test this hypothesis by analyzing the impact of Data Comm implementation on the probability of a mid-air collision in the en route environment.
- Our proposed method builds upon the Integrated Safety Assessment Model (ISAM), an industry-wide accepted safety model developed by the FAA, to provide an in-depth investigation of the role of Data Comm in a mid-air collision.

Introduction

- Because ISAM alone is insufficient to test the impacts of the newly implemented Data Comm, we develop an algorithm that converts fault trees and event sequence diagrams into a Bayesian Belief Network (BBN).

- The proposed model improves the existing method, and brings many of the safety-critical elements, including innovation and new technologies, into a common quantitative framework that can be used for the analysis of new technologies and capabilities under NextGen.

- Data Comm will be introduced into 20 enroute centers by the end of 2019. The proposed model should be useful to the FAA Data Comm Program, the FAA NextGen office, safety analysts, airlines, aviation policy makers and regulators.

Objectives

- Find answers to the following questions:

  (I) how does Data Comm fit into the chain of events that leads to a mid-air collision
  (II) what is the impact of the implementation of Data Comm on the probability of a mid-air collision.

- Explain limitations of existing safety models

- Develop a method for estimating (I) and (II)

- Quantify the impact of Data Comm on the probability of a mid-air collision

Limitations of event-based diagrams

1. Event-based models have a limited notion of causality – non-linear relationships are difficult to model.

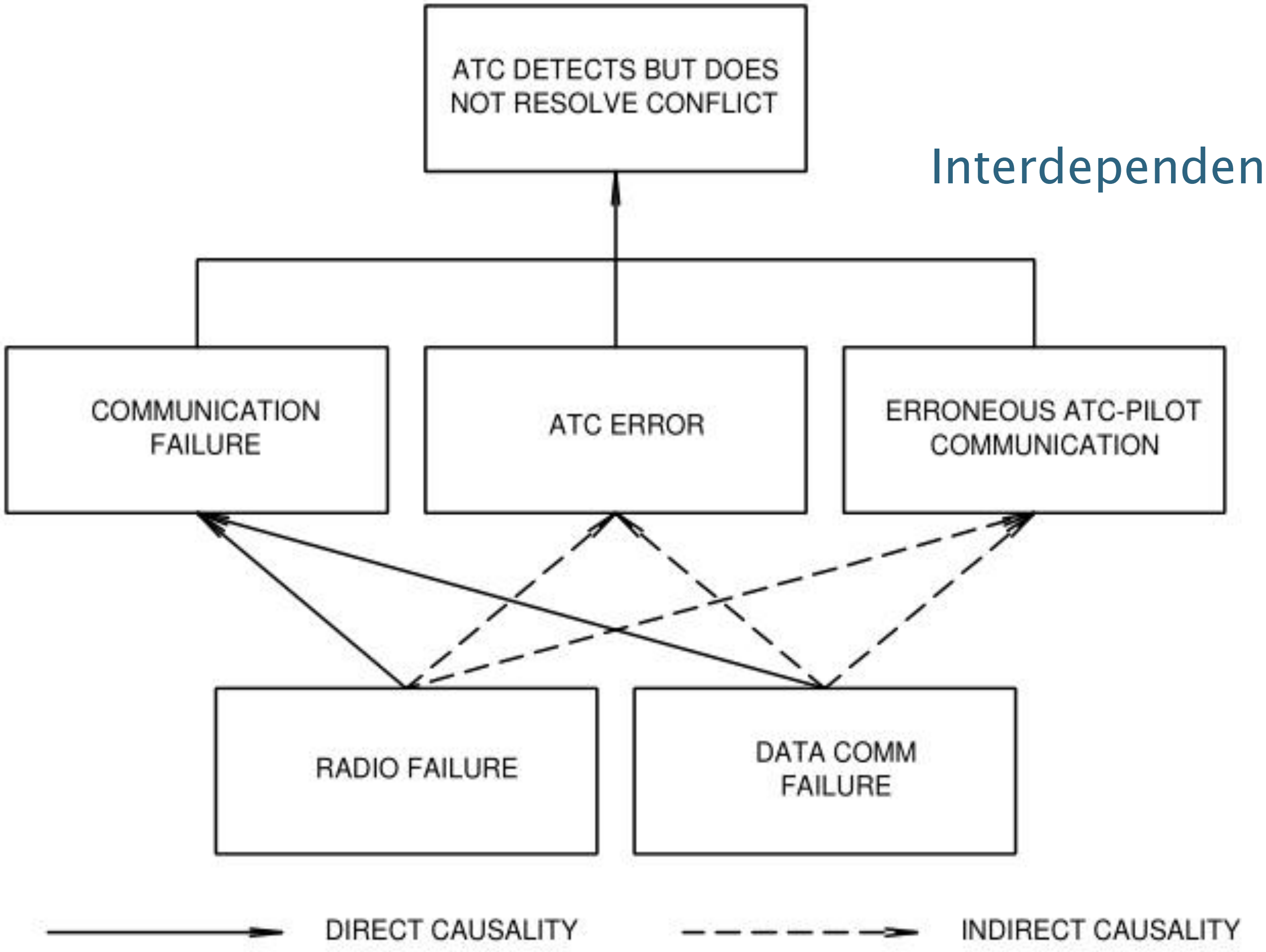
2. Interdependencies and correlations are difficult to model with a fault tree, since a fault tree does not allow upward branching.

3. Interactions between the new technologies and the system can create new categories of accidents that are unobservable in the current system.

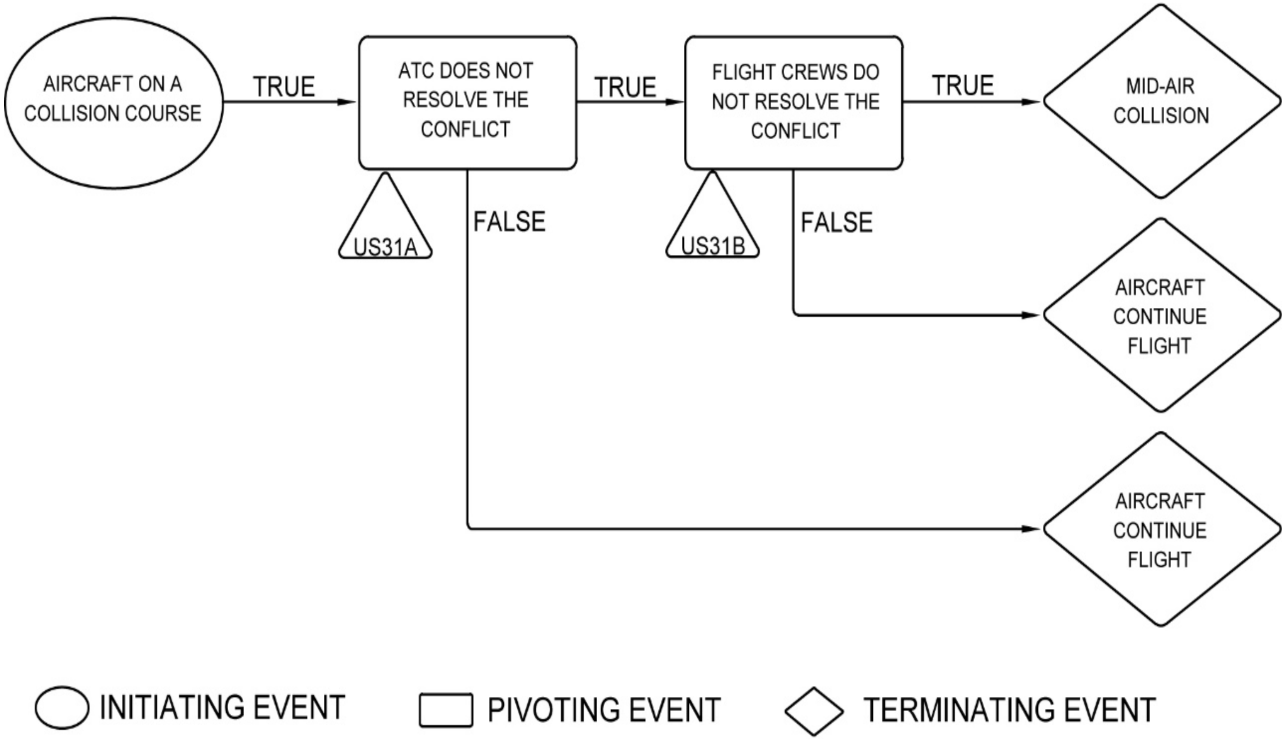
4. Event-based models cannot represent the systemic accident factors such as structural deficiencies in the organization, management deficiencies, and flaws in the safety culture of a company or an industry.

Limitations of event-based diagrams

Interdependencies in the ESD US31a

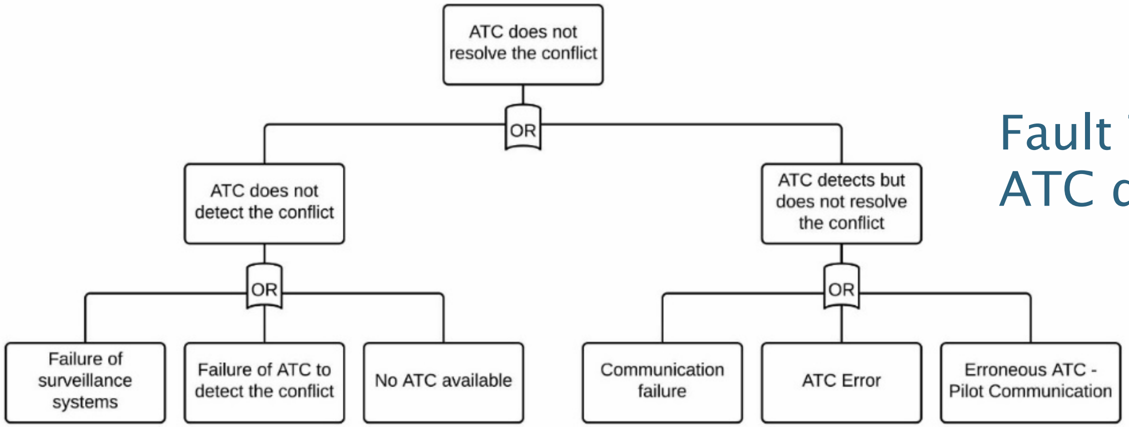


Modeling mid-air collision with the Integrated Safety Assessment Model



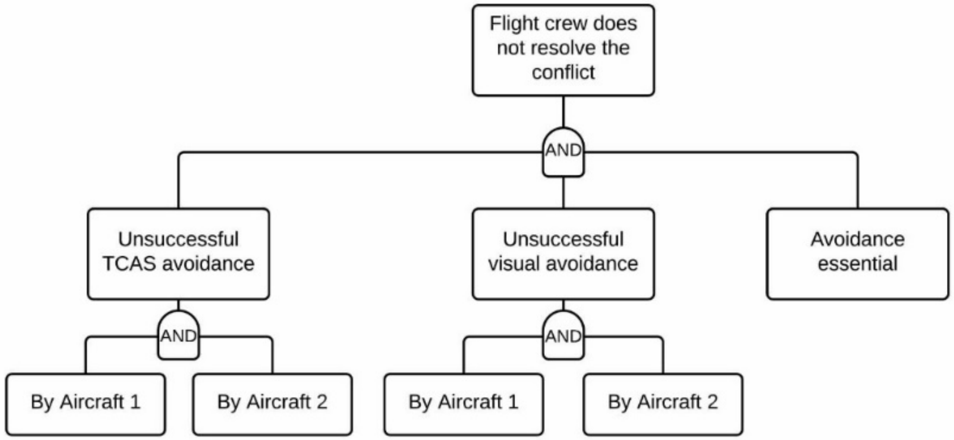
Event Sequence Diagram US31: Aircraft are positioned on a collision course

Modeling mid-air collision with the Integrated Safety Assessment Model



- ATC does not resolve the conflict
  - OR
    - ATC does not detect the conflict
      - OR
        - Failure of surveillance systems
        - Failure of ATC to detect the conflict
        - No ATC available
    - ATC detects but does not resolve the conflict
      - OR
        - Communication failure
        - ATC Error
        - Erroneous ATC - Pilot Communication

Fault Tree US31a:
ATC does not resolve the conflict



- Flight crew does not resolve the conflict
  - AND
    - Unsuccessful TCAS avoidance
      - AND
        - By Aircraft 1
        - By Aircraft 2
    - Unsuccessful visual avoidance
      - AND
        - By Aircraft 1
        - By Aircraft 2
    - Avoidance essential

Fault Tree US31b:
Flight crew does not resolve the confl

Modeling mid-air collision with the Integrated Safety Assessment Model

- The structure of ESD allows us to follow the progression of events from the top (initiating event), through the tree (pivoting events), to the terminating events – a safe outcome, or an incident. ESD is a flowchart with one beginning and several paths leading to different outcomes.
- An ESD does not depict causal relationships, but only presents the progression of events over time. The selection of a path through the tree depends on the outcome of the pivotal events, i.e. the probability predicted by the fault tree. The top node of a fault tree represents a pivotal tree in the ESD. Thus, an FT captures the causal chains that lead to the outcome of a pivotal event.

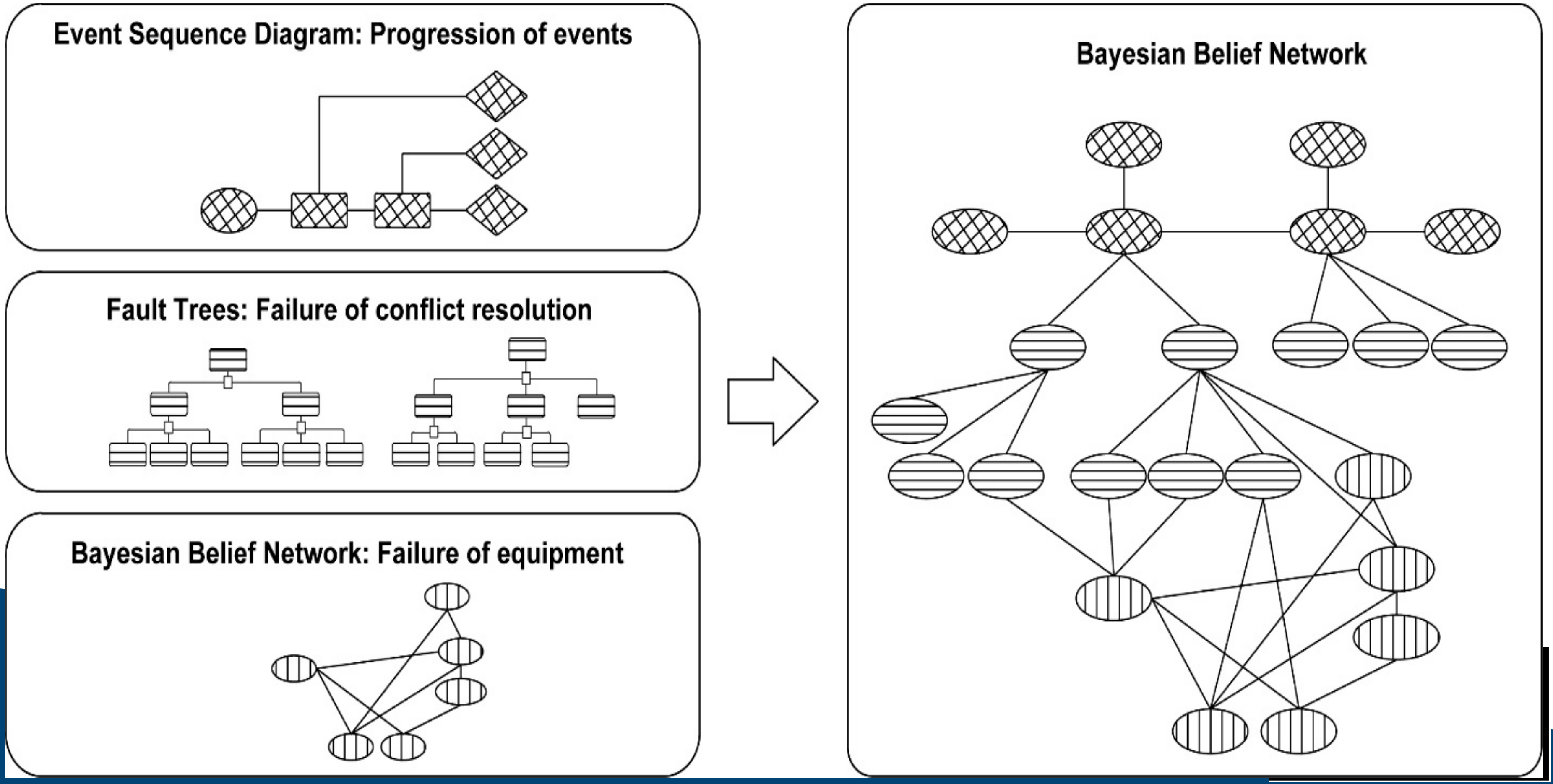
Modeling mid-air collision with Bayesian Belief Network

Conversion Algorithm

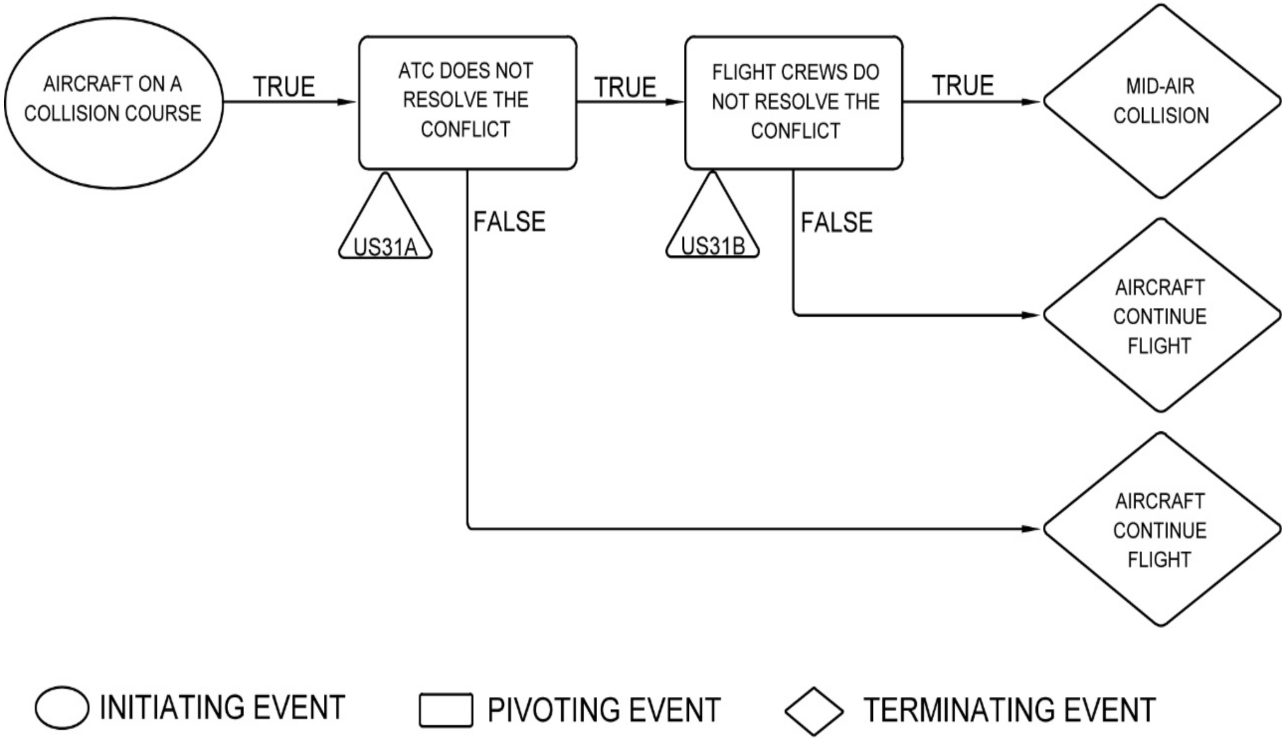
	FAULT TREE	BAYESIAN BELIEF NETWORK	
1	Primary Events	Root Nodes	QUALITATIVE CONVERSION
2	Boolean Gates and Intermediate Events	Intermediate Nodes	
3	Top Event	Leaf Node	
4	Repeating Nodes	A node with multiple children	
5	Components and gates connected in the FT are also connected in the BNN.		
6	Primary event occurrence	Prior Probability	QUANTITATIVE CONVERSION
7	Intermediate event occurrence	Conditional probability table	
8	Boolean Gate	Conditional probability table	

Modeling mid-air collision with Bayesian Belief Network

Conversion Algorithm

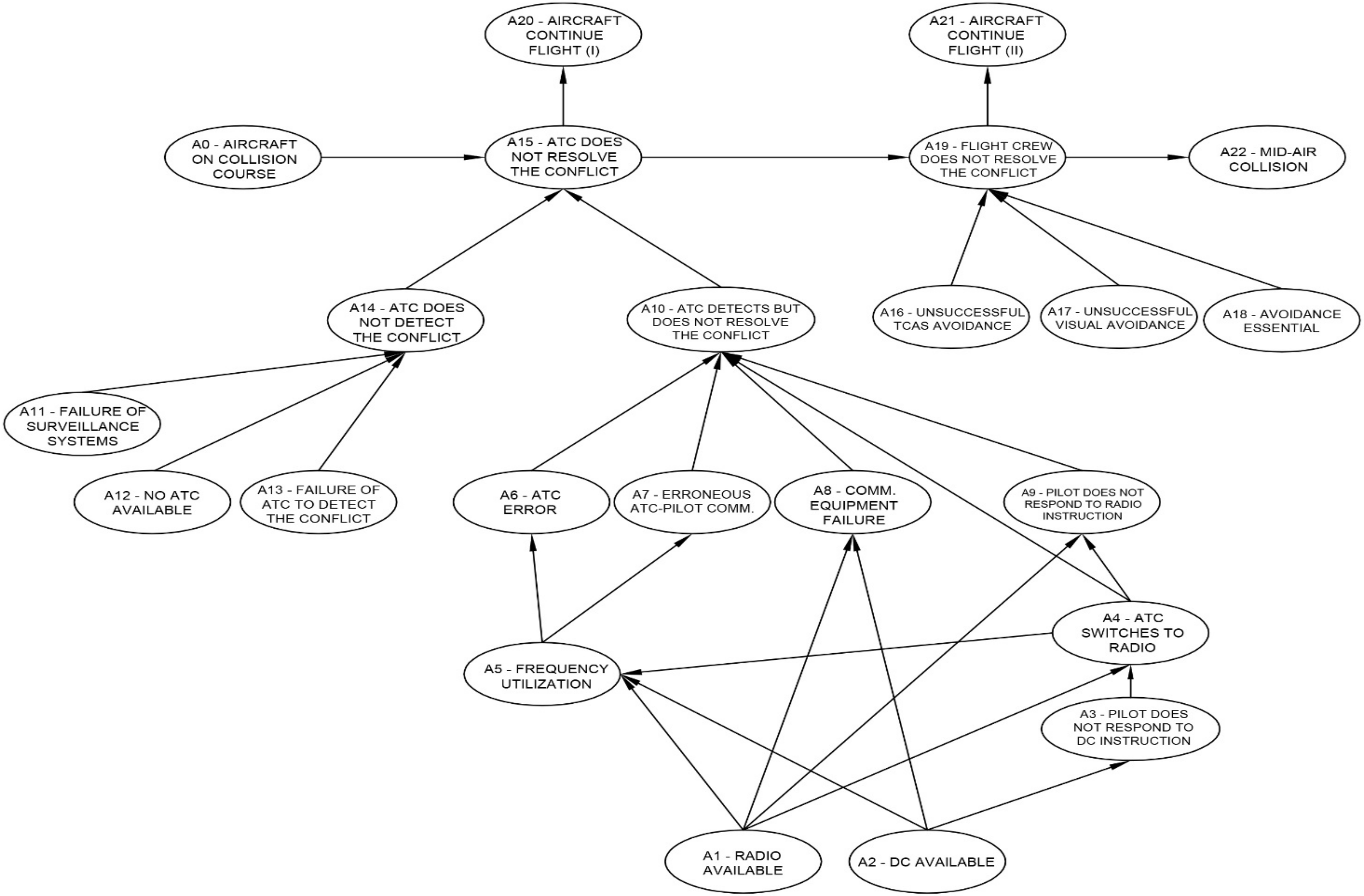


Modeling mid-air collision with the Integrated Safety Assessment Model



Event Sequence Diagram US31: Aircraft are positioned on a collision course

Method | Mid-air Collision Bayesian Belief Network



Method | Mid-air Collision Bayesian Belief Network

BACKGROUND

- The joint probability distribution of all the random variables in the network is reduced to a series of conditional probability distributions of the random variables given their parents. Consequently, it is possible to build a full Bayesian network only by specifying the conditional probability distribution in every node.
- Each node can assume many states, each of which has an associated likelihood quantified either by historical data or expert belief. The likelihoods are contained in the conditional probability tables (CPT). These tables demonstrate a marginal probability of a random variable with respect to the other variables.
- Similarly to the truth tables in the Boolean algebra, we introduce a "belief table" – a set of logical relationships between the ranked variables.

Method | Impact of Data Comm on Mid-air Collisions

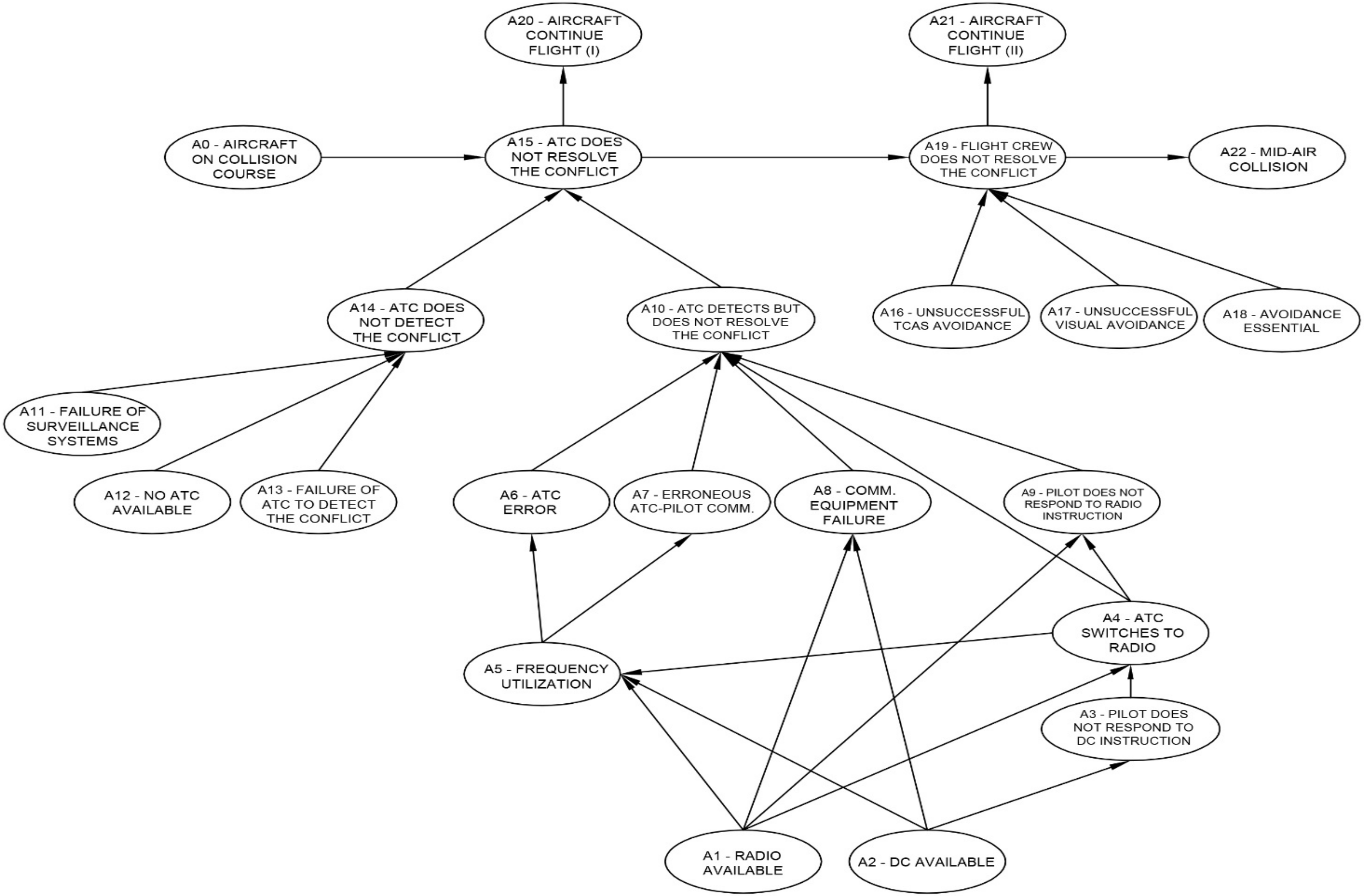
Frequency Utilization: Belief Table

A1 – RADIO AVAILABILITY	A2 – DATA COMM AVAILABILITY	A4 – CONTROLLER SWITCHES TO RADIO	A5 – FREQUENCY UTILIZATION
LOW	TRUE	TRUE	HIGH
		FALSE	MID
	FALSE	TRUE	N / A
		FALSE	HIGH
MID	TRUE	TRUE	MID
		FALSE	LOW
	FALSE	TRUE	N / A
		FALSE	HIGH
HIGH	TRUE	TRUE	MID
		FALSE	LOW
	FALSE	TRUE	N / A
		FALSE	MID

Frequency Utilization: Conditional Probability Table

A1 – RADIO AVAILABILITY	A2 – DATA COMM AVAILABILITY	A4 – CONTROLLER SWITCHES TO RADIO	A5 – FREQUENCY UTILIZATION		
			LOW	MID	HIGH
LOW	TRUE	TRUE	0	0	P(A1=LOW ∧ A2=T ∧ A4=T)
		FALSE	0	P(A1=LOW ∧ A2=T ∧ A4=F)	0
	FALSE	TRUE	0	0	0
		FALSE	0	0	P(A1=LOW ∧ A2=F ∧ A4=F)
MID	TRUE	TRUE	0	P(A1=MID ∧ A2=T ∧ A4=T)	0
		FALSE	P(A1=MID ∧ A2=T ∧ A4=F)	0	0
	FALSE	TRUE	0	0	0
		FALSE	0	0	P(A1=MID ∧ A2=F ∧ A4=F)
HIGH	TRUE	TRUE	0	P(A1=HIGH ∧ A2=T ∧ A4=T)	0
		FALSE	P(A1=HIGH ∧ A2=T ∧ A4=F)	0	0
	FALSE	TRUE	0	0	0
		FALSE	0	P(A1=HIGH ∧ A2=F ∧ A4=F)	0

Method | Mid-air Collision Bayesian Belief Network



Method | Network Variables

Node	Node name	Node type	Source / Calculation
A0	Aircraft on collision course	Root	(FAA, 2016)
A1	Radio available	Root	(Monticone and Liedman, 2005)
A2	DataComm available	Root	(Rakas and Bauranov, 2017)
A3	Pilot does not respond to DC instruction	Intermediate	Conditional Probability Table (CPT)
A4	ATC switches to radio	Intermediate	CPT
A5	Frequency utilization (L,M,H)	Intermediate	CPT
A6	ATC error	Intermediate	CPT
A7	Erroneous ATC – pilot communication	Intermediate	CPT
A8	Communication failure	Intermediate	CPT corresponding to AND-gate
A9	Pilot does not respond to radio instruction	Intermediate	CPT
A10	ATC detects but does not resolve the conflict	Intermediate	CPT corresponding to OR-gate
A11	Failure of surveillance systems	Root	(Borener and Guzhva, 2014)
A12	No ATC available	Root	Assumed 0 in commercial aviation
A13	Failure of ATC to detect the conflict	Root	(Olson and Olszta, 2010)
A14	ATC does not detect the conflict	Intermediate	CPT corresponding to OR gate
A15	ATC does not resolve the conflict	Intermediate	CPT corresponding to OR gate
A16	Unsuccessful TCAS avoidance	Root	(Olszta and Olson, 2010)
A17	Unsuccessful visual avoidance	Root	(Spouge and Perrin, 2005)
A18	Avoidance essential	Root	(Spouge and Perrin, 2005)
A19	Flight crew does not resolve the conflict	Intermediate	CPT
A20	Aircraft continues flight (I)	Leaf	CPT
A21	Aircraft continues flight (II)	Leaf	CPT
A22	Mid-air collision	Leaf	CPT/ Validation: (National Transportation Safety Board, 2017)

AIRPORT
DESIGN
STUDIO

Analysis

Once the network is created and conditional probabilities are defined, the following three scenarios are performed:

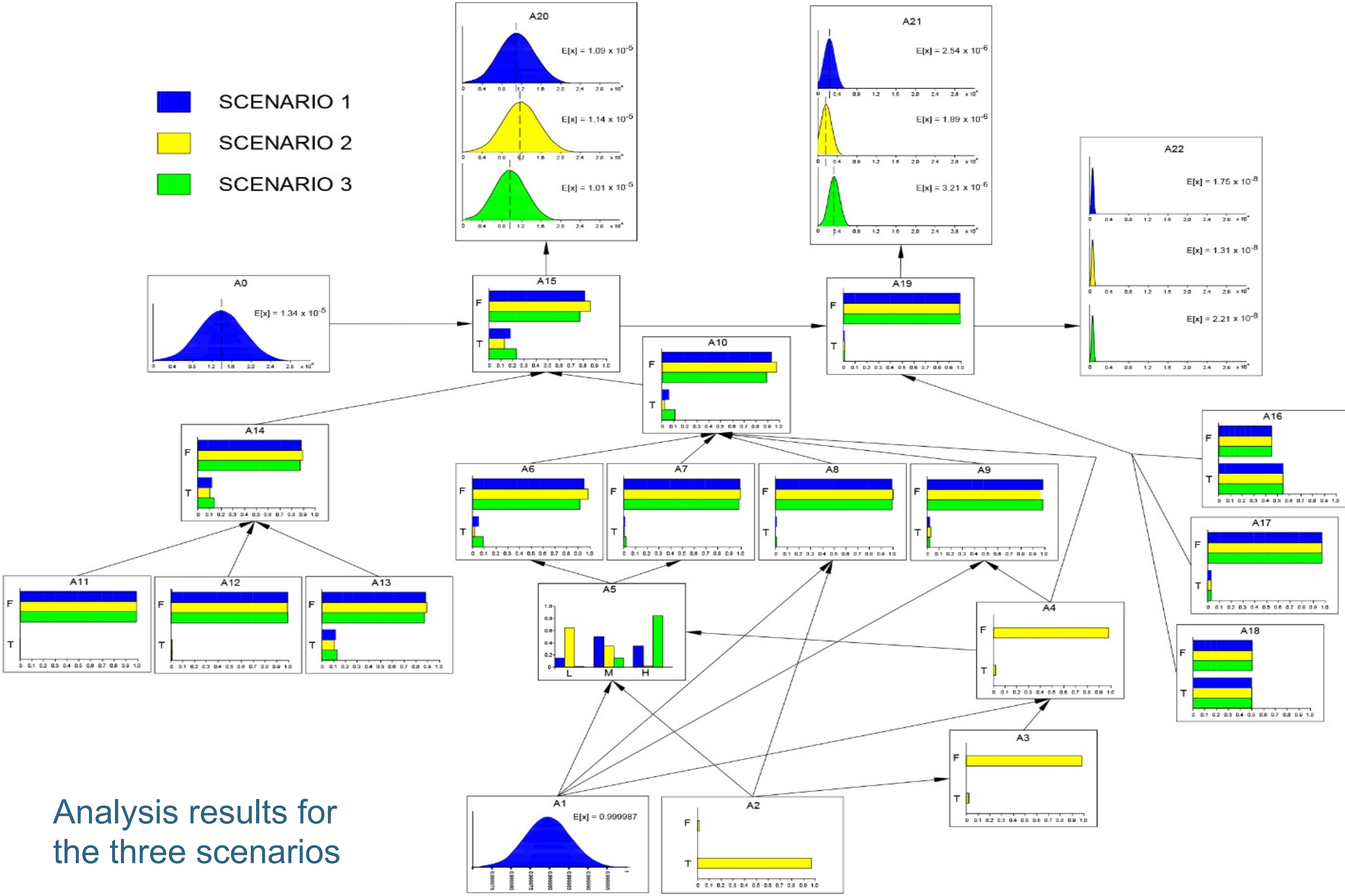
- Scenario 1: Traditional system with the voice communication as the only communication medium. All of the root nodes probabilities are quantified based on this scenario.
- Scenario 2: System with both voice communication and Data Comm in use. Some of the voice messages will be transferred to Data Comm. The question is: how will this transfer impact the probability of a collision?
- Scenario 3: System during unexpected outage of Data Comm. As Data Comm fails, radio becomes the only means of communication. We investigate the impact on the probability of a communication error and, subsequently, the probability of a mid-air collision.

Results | Impact of Data Comm on Mid-air Collisions

🟦 SCENARIO 1

🟨 SCENARIO 2

🟩 SCENARIO 3



Analysis results for the three scenarios

Results | Analysis results for the three scenarios

Node	Node name	Scenario 1	Scenario 2	Scenario 3
A0	Aircraft on collision course	$1.34 * 10^{-5}$	$1.34 * 10^{-5}$	$1.34 * 10^{-6}$
A1	Radio available	0.999987	0.999987	0.999987
A2	Data Comm available	0.99974	0.99974	0
A3	Pilot does not react to Data Comm instruction	N/A	0.1	N/A
A4	ATC switches to radio	N/A	0.1	N/A
A5	Frequency congestion (L,M,H)	(0.31,0.38,0.31)	(0.585, 0.381, 0.034)	(0, 0.15, 0.85)
A6	Erroneous ATC – pilot communication	0.0508	0.0186	0.09037
A7	ATC error	0.0128	0.0061	0.0209
A8	Communication failure	0.00009	$2.37 * 10^{-9}$	0.00009
A9	Pilot does not react to radio instruction	0.01	0.013	0.01
A10	ATC detects but does not resolve the conflict	0.0722	0.0343	0.1197
A11	Failure of surveillance systems	0.00045	0.00045	0.00045
A12	No ATC available	0.01	0.01	0.01
A13	Failure of ATC to detect the conflict	0.1191	0.1028	0.1285
A14	ATC does not detect the conflict	0.1282	0.1122	0.1376
A15	ATC does not resolve the conflict	0.1907	0.1423	0.2409
A16	Unsuccessful TCAS avoidance	0.45	0.45	0.45
A17	Unsuccessful visual avoidance	0.0304	0.0304	0.0304
A18	Avoidance essential	0.5	0.5	0.5
A19	Flight crew does not resolve the conflict	0.00684	0.00684	0.00684
A20	Aircraft continues flight (I)	$1.09 * 10^{-5}$	$1.14 * 10^{-5}$	$1.10 * 10^{-5}$
A21	Aircraft continues flight (II)	$2.54 * 10^{-6}$	$1.89 * 10^{-6}$	$3.21 * 10^{-6}$
A22	Mid-air collision	$1.75 * 10^{-8}$	$1.31 * 10^{-8}$	$2.21 * 10^{-8}$

Discussion: Scenario 1

Scenario 1: Controllers and pilots interact only with radio in the en route environment.

- Around 5% of the interactions are erroneous. These errors, as well as other ATC-specific causes A1-A15 jointly affect the controller's probability to successfully resolve the conflict (variable A6).
- A controller does not resolve conflict in 19% of cases A15. In other words, about every fifth aircraft that is on a collision course will have to rely on its crew and onboard systems to solve the conflict.
- On the other hand, the variable A19 shows that the pilots (and on-board automation) do not resolve the conflict in 0.7% of cases when left to their capacities. This success is accredited mainly to TCAS. If both A15 and A19 are true, and neither the controller nor the flight crews solve the conflict, a mid-air collision A20 occurs. The probability of this occurrence in Scenario 1 is $1.75 * 10^{-8}$ collisions per flight. The results are in line with the official NTSB data (NTSB, 2017).

Discussion: Scenario 2

Scenario 2: Data Comm added as a channel of communication. Controllers and pilots interact in a mixed-mode environment

- The probability of an erroneous communication *A6* will be reduced three-fold, from 5.1% to 1.9%. In other words, out of 60 interactions, only one will be erroneous.
- Consequently, the inability of a controller to resolve the conflict *A15* should decrease from 19% to 14%.
- As a result, the probability of a mid-air collision is reduced from $1.75 * 10^{-8}$ to $1.31 * 10^{-8}$ collisions per flight, a reduction of risk of about 25%.
- If Data Comm was fully implemented today, our analysis results indicate that the probability of a mid-air collision would be 25% lower, compared to the current situation.

Scenario 3:

If Data Comm fails, the risk increases to $2.21 * 10^{-8}$ collisions per flight.

Summary and Conclusions

- The study examined the impact of the Data Comm implementation on the probability of a mid-air collisions in end route environment.
- Using the modeling concepts of Integrated Safety Assessment Model developed (ISAM) by the FAA, we investigated the possible role of Data Comm in the chain of events that leads to a mid-air collision.
- The fault trees and event-sequence diagrams from ISAM were appended with the variables that represent the availability of the communication system.
- However, several newly formed interdependencies between the variables were difficult to model with fault trees and event diagrams.
- The problem was solved by converting the trees to the Bayesian Belief Network.
- A set of conditional probability tables was created to define the states of the variables.

Summary and Conclusions

- A combination of ISAM and BBN, along with the additional variables for newly formed relationships between the existing and new systems, can cover a wide range of accidents, with high level of complexity, without losing the necessary accuracy of the results.

- This method should be sufficient to analyze the safety impacts of the majority of new technologies and capabilities under NextGen.

- If Data Comm was fully implemented today in the en route environment, our analysis results indicate that the probability of a mid-air collision would be 25% lower, compared to the current situation.

Recommendations for Future Work

- Collecting data on the operations of Data Comm and performing a top-down calculation of the overall Data Comm availability.
- As the FAA continues with the implementation of NextGen, it is reasonable to expect a number of new simulations with the NextGen equipment. We suggest a simulation of errors in communication in the mixed-media environment.
- A wider application of Bayesian Networks as a supplement to the ISAM method. A user-friendly holistic model should be developed to assist safety analysts in performing detailed studies about the safety impact of new technologies in NextGen.

Summary | Impact of Data Comm on Mid-air Collisions

Summary

- Texting while driving

- Texting while flying

```
0214z ATC UPLINK   1/1
                STATUS
                  OPEN
REVISED RTE.
CLEARED ROUTE CLEARANCE.
EWR1.
MAINTAIN 3000FT.
 STANDBY
*SEND        LOAD REVIEW>
                  ACCEPT
<REJECT           SEND*
--------------------------
*PRINT              LOG>
```